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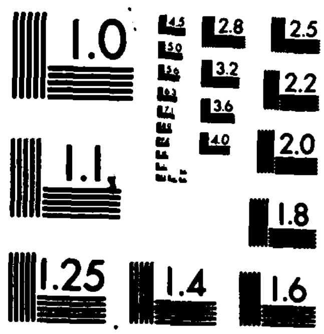

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THE USE OF REFERENCE DATA ON THERMAL CONDUCTIVITY GENERATED BY TPRC/CINDAS

By

C. Y. HO

TPRC/CINDAS SPECIAL REPORT

to

NATIONAL BUREAU OF STANDARDS
Washington, D.C.

and

DEFENSE SUPPLY AGENCY
Alexandria, Virginia

March 1975

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This special report describes the known cases of the use of the reference data on thermal conductivity generated by TPRC/CINDAS for the National Standard Reference Data System and the Department of Defense. The evidence supplied herein clearly shows that the reference data have extensively been used as standards in measurements and in other applications and used in many research and development programs and design calculations, which are essential to the national progress, economy, and defense. The reference data are shown to be extremely useful and the public has ~~been~~ benefited

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20. ABSTRACT (Cont)

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March 1975

CENTER FOR INFORMATION AND NUMERICAL DATA
ANALYSIS AND SYNTHESIS
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FOREWORD

This special report was prepared by the Thermophysical Properties Research Center (TPRC) of the Center for Information and Numerical Data Analysis and Synthesis (CINDAS), Purdue University, West Lafayette, Indiana and submitted to the National Bureau of Standards, Washington, D.C. and to the Defense Supply Agency, Alexandria, Virginia. TPRC is a component of the National Standard Reference Data System and is supported under contract with the U.S. Department of Commerce and under the technical direction of the Office of Standard Reference Data, National Bureau of Standards. CINDAS operates the Thermophysical and Electronic Properties Information Analysis Center (TEPIAC) for the U.S. Department of Defense under contract with the Defense Supply Agency and under the technical direction of the Army Materials and Mechanics Research Center, Watertown, Massachusetts.

This special report is prepared by CINDAS at its own initiative and is submitted concurrently to both of its major sponsors for information and planning purposes. It is hoped that it will prove informative and useful.

PREFACE

Centers involved in a major way in the evaluation of the numerical data of science and technology have a deep concern as to the use their results are put to and the effectiveness of their efforts in the information transfer process. Natural user feedback of such information does not take place to a degree which can be considered significant and inquiry through the medium of special questionnaires has often shown to be at times biased and unreliable. With a view of finding a representative statistical sample as to the nature in which critically evaluated data are used, we made use of the well-known Science Citation Index, a publication of the Institute for Scientific Information, Philadelphia, Pennsylvania. In order to limit the magnitude of the effort involved, in this initial experiment we have limited our study of citations to a narrow field and searched through the Science Citation Index for the years 1967 through the third quarter of 1974. The search yielded 130 citations to the thermal conductivity reference data publications of TPRC. Of these references 119 could be secured and were studied by the author to ascertain the exact manner in which the evaluated data were used. The organization of this report reflects essentially the structure in which the citations could be categorized.

It is felt that the citations encountered in the search represent only the visible part of the iceberg and that the user base for such data is much broader. There are several considerations which come to our attention:

1. Those authors who use evaluated reference data in their research but do not reference such use as long as this fact is not reported in their paper.

2. Those who use reference data extensively in their work which does not result in a publication and therefore there is no opportunity for citation.

3. Those multitudes who use our reference data second hand through reference works such as handbooks, either cite the handbook as a reference or they do not cite at all.

4. There is a tendency on the part of authors to often omit citation of reference works, as opposed to research papers, as they consider the former to be of a more impersonal character.

The eleven sub-groupings under Section II of the report, covering the <u>use</u> of reference data, embody certain implications which could be overlooked by the casual observer. A few brief remarks in this connection may be in order:

1. Relative to the engineering use of reference data it will be noted that in all cases the application is far from routine in character and that success and failure may be of more than casual consequence.

2. Relative to the use of reference data in research and development work, including the area of standardization and calibration, it is clear that the availability of high quality data would have saved considerable time and effort in the program.

3. The fact that there exists an increasing tendency in publications for experimenters to compare their experimental research results against evaluated reference data carries the clear implication that they consider such data of greater degree of credibility than most of the raw data in the literature.

4. The fact that in a significant number of cases evaluated reference data have been advanced prior to the availability of experimental data and later confirmed by elaborate round-robin measurement programs attests to the effectiveness of our procedures and the maturity of the state of the art.

Should it prove desirable or necessary, the type of study presented herein could be conducted in broader scope and in deeper coverage. However, it is felt that the present study, even though somewhat limited, is adequate in scope to provide valid observations and conclusions. The citation coverage is international in representation and involves both basic scientific usage as well as the more applied engineering utility of evaluated reference data.

Y. S. Touloukian
Director

ABSTRACT

This special report describes the known cases of the use of the reference data on thermal conductivity generated by TPRC/CINDAS for the National Standard Reference Data System and the Department of Defense. The evidence supplied herein clearly shows that the reference data have extensively been used as standards in measurements and in other applications and used in many research and development programs and design calculations, which are essential to the national progress, economy, and defense. The reference data are shown to be extremely useful and the public has been benefited greatly by TPRC/CINDAS' undertaking. Furthermore, the report describes TPRC/CINDAS' capability of data estimation and prediction, which has been extensively used to serve not only individual governmental agencies, defense contractors, and industrial organizations, but the Nation as a whole in meeting urgent national needs.

CONTENTS

THE USE OF REFERENCE DATA ON THERMAL CONDUCTIVITY GENERATED BY TPRC/CINDAS

I. INTRODUCTION

Supported by the Office of Standard Reference Data of the National Bureau of Standards, the Defense Supply Agency, and by the Air Force Materials Laboratory (before 1971), the Thermophysical Properties Research Center (TPRC) of the Center for Information and Numerical Data Analysis and Synthesis (CINDAS) at Purdue University has generated recommended reference data on the thermal conductivity of elements, alloys, and compounds, among other physical properties and materials, for the National Standard Reference Data System (NSRDS) and the Department of Defense (DoD).

This report covers the use of the reference data on thermal conductivity only, as an example to show how the recommended reference data generated by TPRC/CINDAS for NSRDS and DoD have been used and by whom, and to show how greatly the public has been benefited by such an undertaking. The use of reference data on other physical properties and materials would be similar.

The recommended reference data on thermal conductivity have been published in three NSRDS publications [1-3] and in Volumes 1 to 3 of the TPRC Data Series [4-6]. Some preliminary results have been given in [7] and [8] and preliminary values on the elements have been presented in the Seventh Conference on Thermal Conductivity [9,10].

The reference data have been used in various ways by numerous users, the majority of which are, of course, not known to us. The known cases must be a very small fraction of all the cases of utilization of these reference data on thermal conductivity. These known cases are described in the next section.

II. USE OF REFERENCE DATA ON THERMAL CONDUCTIVITY

The provision of reference data on thermal conductivity (and other properties) serves many important purposes. Since the knowledge on thermal conductivity is essential for problems involving heat conduction and for the design and operation of various machines and devices for which heat-transfer considerations are important, one of the major uses of these data is that they are used as engineering and design data for industrial and defense applications. Furthermore, thermal conductivity data are used as input data for research and development in many fields, from amorphous semiconductor beam memory to fusion reactor wall erosion.

In thermal conductivity measurements, the provision of reference data on thermal conductivity greatly assists experimental researches to produce accurate data. In recent years over 1,000 research papers per year on thermal conductivity are published in the world literature, and about half of these contain experimental thermal conductivity data. If one assumes that each research paper costs about $30,000 (following the estimation by Dr. L. M. Branscomb [11] for papers in another field), 1,000 research papers will cost about $30 million per year, and those 500 reporting experimental thermal conductivity data will cost about $15 million. Since inaccurate data are useless, the $15 million dollars per year would be wasted if the experimental data produced are inaccurate. Thus, the fact that reference data are used for the production of accurate experimental data proves these data to be very important and useful.

Reference data (and reference materials) are used in thermal conductivity measurements in two ways. First, reference data are used in comparative measurements in which the thermal conductivity of the test material is determined in terms of that of the reference material. Secondly, reference data are used for evaluating and/or checking the accuracy of apparatus designed for absolute measurements. Furthermore, in order to give a greater degree of confidence to the experimental data produced and to assure the reliability of the data, reference data are frequently used for comparison with the experimental data.

For theoretical researchers reference data are used to test their theories or to compare with their theoretically calculated values.

There are other ways, in addition to those mentioned above, in which the recommended reference data on thermal conductivity are used. The known case histories of all these are described below.

1. Reference Data Used as Engineering and Design Data

Bramer, Lurie, and Smith [12] of the TRW Systems, Redondo Beach, California, used our recommended data for the thermal conductivity of pyrolytic graphite [8] and others' data to establish design curves for the design of the inner heat shield to protect, during atmospheric reentry, the capsule containing the radioisotope fuel of a five-year lifetime radioisotope thermoelectric generator of the U.S. Navy's Transit Navigational Satellite.

Almenas [13] of the Nuclear Engineering Program, University of Maryland, College Park, Maryland, used our recommended data for the thermal conductivity of tungsten and uranium dioxide [8] in his design considerations of a spherical W-UO_2 cermet shell reactor operating at a surface temperature of 2800 K as a thermally radiating energy source.

Slabinsk and Smith [14] of the Department of Physics, Case Western Reserve University, Cleveland, Ohio, used our recommended data for the thermal conductivity of magnesium oxide and calcium fluoride [8] in their design considerations of a closed yet demountable lithium vapor cell and discharge lamp with MgO single crystal window.

Pollock [15] of the Tyco Laboratories, Inc., Waltham, Massachusetts, used our recommended data for the thermal conductivity of tungsten and molybdenum [8] in his determination of the material for the growth orifice used in the "edge-defined, film-fed growth" technique to grow void-free filamentary sapphire at high growth rate.

Olivei [16] of the Laboratory of Circuit and Memory, Olivetti, Ivrea, Italy, used our recommended data for the thermal conductivity and specific heat of fused silica, copper, and platinum [8] in his design of a thermal printing matrix head, consisting essentially of a suitable combination of two adjacent thin-film materials, for use in a pulsed electron-beam thermal non-impact printing system.

2. Reference Data Used as Input Data for Research and Development

Behrisch [17] of the Solid State Division, Oak Ridge National Laboratory, Oak Ridge, Tennessee, used our recommended data for the thermal conductivity and specific heat of niobium, vanadium, tantalum, molybdenum, tungsten, boron, graphite, tantalum carbide, and stainless steel 403 [8] to calculate the increase of temperature at the first wall of a Controlled Thermonuclear Reactor in his study of the first-wall erosion in fusion reactors.

Chen [18] of the General Electric Corporate Research and Development Center, Schenectady, New York, used our recommended reference data for the thermal conductivity [4] and compiled data for the specific heat [19] of silicon, molybdenum, tellurium, and selenium in his computer simulation program for the study of high-speed electron beam heating and the subsequent cooling processes in an amorphous semiconductor target of a beam memory.

Weider [20] of the IBM Research Laboratory, San Jose, California, used our recommended reference data for the thermal conductivity of silica [5], compiled data for the specific heat of silica and cadmium sulfide [21], and other data in his calculation of the thermal profile of a three-dimensional heat flow to compare with his measurement by a laser thermoprobe on a thin film which had been applied with a pulse of energy from a GaAs laser.

McClure [22] of Sandia Laboratories, Albuquerque, New Mexico, used our recommended reference data for the thermal conductivity of copper [3] in his calculation of power loss due to cooling by evaporation of copper cathode of an arc in his research on plasma expansion as a cause of metal displacement in vacuum-arc cathode spots.

Wei and Smith [23] of Boeing Scientific Research Laboratories, Seattle, Washington, used our recommended reference data for the thermal conductivity of alumina [5] in their study of the structure of the (0001) surface of α-alumina by low-energy electron scattering using a LEED electron gun.

Hesse and Sparrow [24] of the Heat Transfer Laboratory, Department of Mechanical Engineering, University of Minnesota, Minneapolis, Minnesota, used our recommended reference data for the thermal conductivity of helium [6] in their calculations of the Nusselt number and Prandtl number for comparison with their experimental results on natural convection heat transfer from high-temperature horizontal wires to gases.

Waleh and Zebound [25] of the Department of Physics and Astronomy, Louisiana State University, Baton Rouge, Louisiana, used our recommended reference data for the thermal conductivity of molybdenum [2] at high temperature to help them in deriving the effective number of conduction electrons per atom for molybdenum in their research on the supercooling and thermal conductivity in superconducting molybdenum.

Jin and Purdy [26] of the Department of Metallurgy and Materials Science, McMaster University, Hamilton, Ontario, Canada, used our estimated values for the thermal conductivity of molten iron [4] in their research on the steady controlled solidification of an Fe-8% Ni alloy.

Fletcher, Friedman, and Scott [27] of the Department of Physics, Queen's University, Kingston, Ontario, Canada, used our recommended reference data for the thermal conductivity of liquid and gaseous helium [1], in the environment of which they measured the Righi-Leduc coefficient and Hall coefficient of copper, silver, and gold.

Jones [28] of Tube Investments Research Laboratories, Saffron Walden, Essex, England, used our estimated values for the thermal conductivity of molten magnesium [2] in his determination of the freezing time of magnesium droplets generated by rotary atomization prior to impact to the walls of a chamber in his research on the cooling, freezing, and substrate impact of droplets formed by rotary atomization. Jones [29] also used our recommended data for the thermal conductivity and thermal diffusivity of aluminum and steel [8] in his calculation of the solidification constant for comparison with his measurement in his study of plane-front freezing from a chill.

Cullis, Nevell, and Trimm [30] of the Department of Chemical Engineering and Chemical Technology, Imperial College, London, England, used our recommended reference data for the thermal conductivity of methane, oxygen, and carbon dioxide [6] in their calculation of power dissipation by a catalyst bead system in an atmosphere of each of these gases in their measurement of the rates of heterogeneous catalytic reactions using a calorimetric bead system.

McPherson [31] of the Department of Materials Engineering, Monash University, Clayton, Victoria, Australia and Division of Inorganic and Metallic Structure, National Physical Laboratory, Teddington, England, used our recommended reference data for the thermal conductivity of oxygen [6] and our recommended data for the density of alumina [8] in the estimation of interfacial energies of α-Al_2O_3 and γ-Al_2O_3 and in the calculation of the thermal history of Al_2O_3 particles during solidification in an oxygen stream, in his research on the formation of metastable phases in flame- and plasma-prepared alumina.

Jones and Renz [32] of the Department of Technical Thermodynamics, Rheinisch-Westfälische Technical Institute, Aachen, West Germany, used our recommended reference data for the thermal conductivity of carbon tetrachloride [6] in their study of the turbulent flow of a mixture of carbon tetrachloride vapor and air over a vertical plate onto which the vapor condenses.

Ohashi and Fischer [33] of the Max Planck Institute for Iron Research, Stuttgart, West Germany, used our estimated values for the thermal conductivity of molten iron [9] in their calculation of the course of undercooling of the melt at the solidification front in their study of the iron solidification kinetics.

Moizhes and Nemchinskii [34] of the Institute of Semiconductors, Academy of Sciences of the USSR, Leningrad, USSR, used our recommended data for the thermal conductivity of tungsten [8] in their calculation of the parameters of an arc at a temperature of about 4000 K in argon atmosphere on a tungsten surface at different arc current, in their research on the behavior of a high-pressure arc with a refractory cathode.

3. Reference Data Used as Standards in Comparative Measurements of Thermal Conductivity

Allen [35] of Donald W. Douglas Laboratories, McDonnell-Douglas Astronautics Co., Richland, Washington, used our recommended data for the thermal conductivity of copper [8] as standard values in his comparative measurements of the thermal conductivity of tantalum carbide and tungsten-samarium oxide using his new apparatus, which was designed for the measurement of the thermal conductivity of nuclear fuels and heat source materials using an electron beam technique.

Thernquist and Wang [36] of the Department of Materials Science and Engineering, University of Florida, Gainesville, Florida, used our recommended reference data for the thermal conductivity of aluminum [1] as standard values in their comparative measurements of the thermal conductivity of doped indium.

Molgaard and Smeltzer of the Department of Metallurgy and Materials Science, McMaster University, Hamilton, Ontario, Canada, used our recommended reference data for the thermal conductivity of Armco iron [1] as standard values in their comparative measurements of the thermal conductivity of a Pt-13% Rh alloy [37] and magnetite and hematite [38] and of the thermal contact resistance at gold foil surfaces [39].

Bogomolov, Smirnov, and Shadrichev [40] of the Institute of Semiconductors, Academy of Sciences of the USSR, Leningrad, USSR, used our recommended reference data for the thermal conductivity of fused quartz [1] as standard values in their comparative measurements of the thermal conductivity of rutile. Smirnov, Shadrichev, and Kutasov [41] similarly used our recommended reference data on fused quartz [1] as standard values in their comparative measurements of the thermal conductivity of doped bismuth telluride.

4. Reference Data Used as Standards for Evaluating and/or Checking the Accuracy of Apparatus Designed for Absolute Measurements of Thermal Conductivity

Carmichael, Jacobs, and Sage of the Chemical Engineering Laboratory, California Institute of Technology, Pasadena, California, used our recommended reference data for the thermal conductivity of helium [1] and others' data to check the accuracy of their apparatus in their measurements of the thermal conductivity of propane [42], n-pentane [43], and a mixture of methane and n-butane [44].

Erdman of the University of Virginia, Charlottesville, Virginia, and Schilmoeller of the University of Notre Dame, Notre Dame, Indiana, used our recommended reference data for the thermal conductivity of aluminum [9] to evaluate the accuracy of their apparatus [45], which was designed for measuring thermal conductivity by a dynamic technique.

Forman [46] of NASA Lewis Research Center, Cleveland, Ohio, used our recommended reference data for the thermal conductivity of aluminum oxide [5] to evaluate the accuracy of his novel method of making high-temperature thermal conductivity measurements by using a lithium-filled heat pipe in series with a gas-gap variable heat conductance unit as a heat source.

Gulari, Brown, and Pings [47] of the Division of Chemistry and Chemical Engineering, *California Institute of Technology*, Pasadena, California, used our recommended reference data for the thermal conductivity [6] and specific heat [48] of acetone, carbon tetrachloride, ethanol, n-hexane, methanol, and toluene to calculate thermal diffusivity values for evaluating the accuracy of their apparatus, which was designed for measuring thermal diffusivity and mutual diffusion coefficient by a quasi-elastic light scattering technique.

Schriempf [49,50] of the U.S. Naval Research Laboratory, Washington, D.C., used our recommended reference data for the thermal conductivity of mercury [4] to derive the values for the thermal diffusivity of mercury, which were used to evaluate the accuracy of his apparatus for measuring thermal diffusivity of liquid metals at elevated temperatures by a laser flash technique.

Saxena of the Department of Energy Engineering, University of Illinois at Chicago Circle, Chicago, Illinois, and Saxena of the Graduate Center for Cloud Physics Research, University of Missouri, Rolla, Missouri [51] used our recommended reference data for the thermal conductivity of hydrogen, deuterium, and nitrogen [6] to evaluate the accuracy of their apparatus, which was designed for measuring thermal conductivity by a column method.

Morrison and Sturgess [52] of the Los Alamos Scientific Laboratory, Los Alamos, New Mexico, used our recommended reference data for the thermal diffusivity of iron to check the accuracy of their apparatus, and used also our recommended reference data for the thermal conductivity of zirconium and niobium [2] to compare with their results on the thermal conductivity of zirconium carbide and niobium carbide.

Menden, Rao, and Tee [53] of the Department of Physics, Delhousie University, Halifax, Nova Scotia, Canada, used our recommended reference data for the thermal conductivity of copper and silver [1] to check the accuracy of their thermal conductivity apparatus.

Helwig and Albers [54] of the Institute of Experimental Physics, University of Saarlandes, Saarbrucken, West Germany, used our recommended reference data for the thermal conductivity of fused quartz [1] to check the accuracy of their thermal conductivity apparatus.

Chistov, Belyaev, and Butsev [55] of the Kurnakov Institute of General and Inorganic Chemistry, Academy of Sciences of the USSR, Moscow, USSR, used our recommended reference data for the thermal conductivity of fused quartz [1] to check the accuracy of their thermal conductivity apparatus.

5. Reference Data Used for Comparison with Experimental Data to Assure the Latter's Reliability

Butherus and Storvick of the Department of Chemical Engineering, University of Missouri, Columbus, Missouri, used our recommended reference data for the thermal conductivity of nitrogen gas [3] to compare with their experimental results [56].

Feith of the Nuclear Materials and Propulsion Operation, General Electric Company, Cincinnati, Ohio, compared his experimental results on the thermal conductivity of powdered thoria of 75% theoretical density in various atmospheres [57] against our recommended reference data for the thermal conductivity of high-density sintered thoria [1].

Fulkerson, Moore, Williams, Graves, and McElroy of the Metals and Ceramics Division, Oak Ridge National Laboratory, Oak Ridge, Tennessee, used our recommended data for the thermal conductivity of silicon [8] to compare with their experimental results [58]. Godfrey, McElroy, and Ardary used our recommended reference data for the thermal conductivity of amorphous carbon, nitrogen, and argon [3] to calculate the thermal conductivity of fibrous carbon insulation for comparison with their experimental results on oriented fibrous carbon insulation in nitrogen and argon [59,60]. Moore, Williams, and Graves compared their experimental results on the thermal conductivity of molybdenum [61] against our recommended reference data [2].

Hoch and Jun of the Department of Materials Science and Metallurgical Engineering, University of Cincinnati, Cincinnati, Ohio, compared their experimental results on the thermal conductivity of tungsten [62] against our recommended reference data [1].

Holcombe, Smith, Lore, Duerksen, and Carpenter [63] of the Oak Ridge Y-12 Plant, Nuclear Division, Union Carbide Corporation, Oak Ridge, Tennessee, derived thermal conductivity values for β-rhombohedral boron from their experimental results on thermal diffusivity and compared the derived thermal conductivity values against our recommended reference data [4].

Slack of the General Electric Research and Development Center, Schenectady, New York, and Austerman of Autonetics, North American Rockwell, Anaheim, California, used our recommended reference data for the thermal conductivity of beryllium oxide [1] to compare with their experimental results [64]. They also referred to our recommended reference data for copper [1] in their comparison of the room-temperature thermal conductivity of beryllium oxide with that of copper [64].

Sundstrom and Yu-Der Lee of the Department of Chemical Engineering and the Institute of Materials Science, University of Connecticut, Storrs, Connecticut, used our recommended reference data and compiled data for the thermal conductivity of aluminum oxide, magnesium oxide, calcium oxide, and glass [5] in their calculation of the thermal conductivity of polystyrene and polyethylene filled with particulates of those materials using theoretical models for two-phase media and compared the calculated values with their experimental results [65].

Weissman of the Mound Laboratory, Monsanto Research Corporation, Miamisburg, Ohio, used our recommended reference data for the thermal conductivity of neon [6] in his calculation of the self-diffusion coefficient of neon and compared the calculated values with his experimental results [66].

Laubitz of the Division of Physics, National Research Council of Canada, Ottawa, Canada, compared his experimental results on the thermal conductivity of copper [67] and of silver and gold [68] against our recommended reference data [1]. Matsumur and Laubitz used our recommended reference data for the thermal conductivity of silver [1] to compare with their experimental results [69].

Cook and Van der Meer of the Division of Physics, National Research Council of Canada, Ottawa, Canada, compared their experimental results on the thermal conductivity of gold [70] against our recommended reference data [1]. Cook, Laubitz, and Van der Meer used our recommended reference data for the thermal conductivity of lead [2] to compare with their experimental results [71].

Brain of the Department of Mechanical Engineering, University of Glasgow, Scotland, U.K., compared his experimental results on the thermal conductivity of steam [72] against our recommended reference data [1].

Irving, Jamieson, and Paget of the National Engineering Laboratory, Glasgow, Scotland, U.K., used our recommended reference data for the thermal conductivity of air [6] to compare with their experimental results [73].

Wolter and Trowell [74] of the Applied Chemistry Division, Atomic Energy Research Establishment, Harwell, Berkshire, England, U.K., derived thermal conductivity values for porous copper from their experimental results on the thermal diffusivity of porous copper and compared the derived values against our recommended data [8].

Böhm and Wachtel [75] of the Max Planck Institute for Metal Research, Institute of Metallurgy, Stuttgart, West Germany, compared their experimental results on the thermal conductivity of aluminum and iron against our recommended reference data [1].

Eichler, Salje, and Stahl of the Physical Institute, Technical University of Berlin, Berlin, West Germany, used our recommended reference data for the thermal conductivity [6] and specific heat [48] of glycerin and methanol in their calculation of the relaxation time for comparison with their measured relaxation time, from which the thermal diffusivity was determined using a technique of spatially periodic temperature distribution induced by laser light [76].

Duggin of the Division of Physics, National Standards Laboratory, Commonwealth Scientific and Industrial Research Organization, Chippendale, N.S.W., Australia, compared his experimental results on the thermal conductivity of liquid mercury [77] and of aluminum and platinum [78] against our recommended reference data [1].

Chuah and Ratnalingam [79] of the School of Physics and Mathematics, University of Science of Malaysia, Penang, Malaysia, used our estimated values for the thermal conductivity of ytterbium [9] to compare with their experimental results.

Sugawara of the Department of Mechanical Engineering, Yamagata University, Yamagata, Japan, compared his experimental results on the thermal conductivity of fused quartz [80, 81] against our recommended reference data [1].

Fujii and Osako of the Geophysical Institute, University of Tokyo, Tokyo, Japan, used our recommended reference data for the thermal conductivity of air [6] in their calculation of the thermal conductivity of the solid and the aspect ratio of the pores from the effective thermal conductivity at one atmospheric pressure, the thermal conductivity of the fluid in the pores, and the thermal conductivity in vacuum for comparison with their experimental results on three lunar rocks and a terrestrial basalt [82].

Nath and Chopra of the Department of Physics, Indian Institute of Technology, New Delhi, India, compared their experimental results on the thermal conductivity of thin copper films [83, 84] against our recommended reference data for the thermal conductivity of bulk copper [1].

Tyagi and Mathur of the Solid State Physics Division, Indian Institute of Technology, New Delhi, India, used our recommended reference data for the thermal conductivity of nickel [2, 9] to compare with their experimental results [85].

Chechel'nitskii of the D. I. Mendeleev All-Union Scientific Research Institute of Metrology, Leningrad, USSR, compared his experimental results on the thermal conductivity of fused quartz [86] against our recommended reference data [1].

Vermogradskii and Chekhovskoi of the Institute of High Temperature, Academy of Sciences of the USSR, Moscow, USSR, used our recommended reference data for the thermal conductivity of tungsten [1] to compare with their experimental data [87].

6. Reference Data Used for Testing Theories and/or Comparison with Theoretically Calculated Values

Dymond of the Department of Chemistry, University of Glasgow, Scotland, U.K., and Alder of the Lawrence Radiation Laboratory, University of California, Livermore, California, compared their theoretically calculated values for the thermal conductivity of argon [88] *against our recommended reference* data [1] to test their proposed interatomic potential for argon.

White [89] of the Division of Physics, National Standards Laboratory, CSIRO, Chippendale, N.S.W., Australia, used our recommended reference data for the thermal conductivity of aluminum, copper, iron, platinum, and tungsten [1] in his calculation of the electronic thermal conductivity values, from which he derived the values of the Lorenz ratio for these metals to compare with the theoretical value of the Lorenz ratio.

Shimizu and Sakoh [90] of the Department of Applied Physics, Nagoya University, Nagoya, Japan, used our recommended reference data for the thermal conductivity of iron [4] to compare with their theoretically calculated values for the thermal conductivity of b.c.c. iron using a simple band model by averaging electron-phonon interactions over the Fermi surface.

Viswanath and Mathur [91] of the Department of Chemical Engineering, Indian Institute of Science, Bangalore, India, used our recommended reference data for the thermal conductivity of some metals in the liquid state [1,2] to compare with their predicted values from a correlation based upon the cell theory of liquids.

Bezrukova, Men', and Sergeev [92] of D.I. Mendeleev All-Union Metrology Research Institute, Leningrad, USSR, used our recommended reference data for the thermal conductivity of fused quartz [1] to compare with their theoretically calculated thermal conductivity values without photon contribution, from which the photon conductivity in fused quartz was derived.

7. Reference Data Used as a Guide for the Development of High-Temperature Thermal Conductivity Standards and Finally Confirmed and Used as Standards

From 1965 to 1973 a major international program on the development of high-temperature thermal conductivity standards was conducted [93-98]. The program was sponsored by the U.S. Air Force Materials Laboratory, Wright-Patterson Air Force Base, Dayton, Ohio with Dr. M. L. Minges acting as project engineer, and it was coordinated by the Arthur D. Little, Inc., with Dr. A. E. Wechsler as the principal investigator. In this program 22 materials were initially selected for screening as candidates for high-temperature thermal conductivity standards. Of these, five (tungsten, aluminum oxide, thorium dioxide, RVD graphite, and AXM-5Q graphite) were then selected for an initial field test program involving six laboratories in the United States. Finally two of the materials (tungsten and AXM-5Q graphite) were regarded as the best available and selected for more extensive evaluation in an expanded international measurement program which involved 18 laboratories, nine in Europe and nine in the United States.

Of the five materials selected as candidates for potential thermal conductivity standards, we had generated recommended thermal conductivity reference data for three (tungsten, aluminum oxide, and thorium dioxide) [1]. Throughout this program our recommended reference data were used extensively by them as a guide for the development, and against our recommended reference data they compared the round-robin experimental results produced by the laboratories involved, and our reference data were verified and confirmed in their evaluation and analysis [96-98].

For tungsten, which is one of the two materials of their final selection as standard materials*, they finally concluded [97, 98], after eight years' effort and 18 international laboratories' measurements, that our TPRC's recommended reference data [1, 3] truly represent the thermal conductivity of tungsten within ±5%, and our data were thus used as standards.

If they had adopted our recommended reference data for tungsten in the beginning of this program, a great deal of effort would have been saved.

Parallel to the above program, there was another cooperative measurement program conducted in Europe from 1967 to 1973 on the thermophysical properties of materials at high temperatures, which was sponsored by the Advisory Group for Aerospace Research and Development (AGARD) of the North Atlantic Treaty Organization (NATO) and was coordinated by Professor E. Fitzer of the Institute for Chemical Technology, University of Karlsruhe, West Germany [99]. In the thermal conductivity phase of this program, our recommended reference data for copper, gold, platinum, tungsten, and aluminum oxide [1, 4] were similarly used as a guide for the program, and against our recommended reference data they extensively compared the round-robin experimental results from the many laboratories participated, and our reference data were verified and confirmed [99].

In another round-robin measurement program coordinated by Mr. C. F. Lucks of the Instrumentation Division, Battelle Memorial Institute, Columbus, Ohio, for the

* We have not generated recommended reference data for the thermal conductivity of AXM-5Q graphite, which is the other selected material.

generation of standard values for the thermal conductivity of Armco iron [100], our recommended reference data for Armco iron [3] were adopted.

8. Reference Data Used for Correlation or for the Derivation of Values for Other Properties

Lange of the Institute for Iron Metallurgy, Rheinisch-Westfälischen Technical Institute, Aachen, West Germany, used our recommended reference data for the thermal conductivity of solid iron and the estimated values for the molten iron [1,9] in his calculation of the thermal diffusivity values for iron between room temperature and 1700 C [101]. He also used our recommended reference data for the thermal conductivity of solid nickel [2,9] at the highest temperature in his estimation of the thermal conductivity and the Prandtl number of molten nickel at the melting point [102], and used our estimated thermal conductivity values for molten iron [9] in his calculation of the Prandtl number of molten iron at temperatures between the melting point of iron and 2000 C [102].

Chang [103] of the Lowell Technological Institute, Lowell, Massachusetts, considered our recommended reference data for the thermal conductivity of gases [3] as being of the highest possible reliability and used our data to develop a nomograph, which can be used to find the thermal conductivity values for gases at atmospheric pressure and at any temperature.

Kokkas [104] of the RCA Laboratories, Princeton, New Jersey, found in the course of developing techniques for the thermal analysis of semiconductor structures in his work on high performance integrated circuits that it became necessary to express in closed form the dependence of the thermal conductivity of silicon and germanium on the temperature. He thus used our recommended reference data for the thermal conductivity of silicon and germanium [3] to derive two empirical relationships between thermal conductivity and temperature for silicon and germanium and found that his expressions accurately represent our data.

Millstein [105] of the Central Research Department, Experimental Station, E. I. du Pont de Nemours & Co., Inc., Wilmington, Delaware made the first measurement of the thermal conductivity of ruthenium dioxide, which is metallic, and used the expression for electronic thermal conductivity given in our publication [2] to fit his experimental data.

Minges [97,98] of the Air Force Materials Laboratory, Wright-Patterson Air Force Base, Dayton, Ohio used two semi-empirical relationships between the electrical conductivity and thermal conductivity of graphite given in our publication [2] to calculate the thermal conductivity of AXM-5Q graphite from electrical conductivity data, which was for checking the consistency of the experimental electrical conductivity results with the results on the thermal conductivity in his program for the development of high-temperature thermal conductivity standards discussed in the last section.

9. Reference Data Used for Substantiating Observations and Statements or for Discussing Experimental Results

Slack [106] of the General Electric Research and Development Center, Schenectady, New York referred to our recommended reference data for the thermal conductivity of nonmetallic crystals such as aluminum oxide and silicon dioxide [1] to substantiate his observation that nonmetallic crystals with large number of atoms per primitive unit cell like aluminum oxide and silicon dioxide are not expected to have high thermal conductivity at room temperature. He [106] also used our recommended reference data for the thermal conductivity of graphite [2] to substantiate his observation that the thermal conductivity of graphite in the direction perpendicular to the c-axis is much higher than that in the other direction and has values up to 20 W cm^{-1} K^{-1} at 300 K.

Laubitz of the Division of Physics, National Research Council of Canada, Ottawa, Canada and McElroy of the Metals and Ceramics Division, Oak Ridge National Laboratory, Oak Ridge, Tennessee [107] referred to our recommended reference data and the compiled existing experimental data [1,2] to substantiate their statement that thermal conductivity measurements at high temperatures have gone beyond the random-number generation stage but this case is by no means apparent from inspection of the existing experimental data.

Genter and Grosse [108] of the Germantown Laboratories, Inc., an Affiliate of the Franklin Institute, Philadelphia, Pennsylvania used the information contained in our publications [7,9] to substantiate their statement that no information is available for the thermal conductivity of molten calcium, strontium, and barium, and hence it is justified for them to measure the electrical conductivity of molten barium for the calculation of its thermal conductivity from the melting point to about 1500 K.

Dresher and Pike [109] of the Fibrous Ceramic Materials Section, Union Carbide Corp. in their work on ceramic fibrous materials for high-temperature insulation used our publication [1] as one of six references for their statement that at high temperatures the thermal conductivity of solids is much greater than that of all relevant gases except hydrogen and helium.

Schriempf [110] of the U. S. Naval Research Laboratory, Washington, D. C. referred to our compiled experimental data on the thermal conductivity of liquid metals [1,2] which show the lack of agreement among results from various laboratories to substantiate his statement that experimental measurement of the thermal conductivity of liquid metals is not a simple matter.

Storms and Wagner [111] of the Los Alamos Scientific Laboratory, Los Alamos, New Mexico used our recommended reference data for the thermal conductivity of niobium and zirconium [3] in the discussion of their experimental results on niobium carbide and zirconium carbide.

Dietze of the Semiconductor Branch, Siemens AG, Munchen, West Germany and Hunt and Sawer of the Solid State Research and Development, Dow Corning Corp., Hemlock, Michigan [112] used our recommended reference data for the thermal conductivity of silicon [4] in their discussion of the properties of silicon for semiconductor device technology.

Klemens of the Department of Physics and Institute of Materials Science, University of Connecticut, Storrs, Connecticut and Greenberg of the U.S. Army Electronics Command, Fort Monmouth, New Jersey [113] referred to our publication [5] for information on the thermal conductivity of amorphous solids in their discussion on the radiative heat transfer through composite materials.

Giraudie [114] of the Central Laboratory of Electric Industries, Fontenay-aux-Roses, Hauts-de-Seine, France referred to our recommended reference data and the compiled experimental data for the thermal conductivity of quartz [1] in his discussion of the dependence of property data on the physical characteristics and chemical impurities of specimens.

McLaughlin and Pittman [115] of the Department of Chemical Engineering and Chemical Technology, Imperial College, London, England stated that our compiled data on the thermal conductivity of liquid toluene [1] show that the trend over the years has been towards lower values of thermal conductivity.

Duggins [116] of the Division of Physics, National Standards Laboratory, Chippendale, N.S.W., Australia referred to our publications [1,2] as having summarized the discrepancies existing in the thermal conductivity data on liquid metals.

Tyagi and Mathur [117] of the Solid State Physics Division, Indian Institute of Technology, New Delhi, India referred to our findings on the behavior of thermal conductivity across the Curie temperature of a ferromagnetic metal [9] in the discussion of their experimental results on the thermal conductivity of cobalt.

10. Reference Data Compilations Used as Data Sources

Flynn [118] of the Institute for Applied Technology, National Bureau of Standards, Washington, D.C., in his discussion of the reference standards for thermal conductivity, referred to our publications [1,2,9,10] as the sources of standard reference data for standard reference materials aluminum, copper, iron, Armco iron, lead, silicon, tungsten, aluminum oxide, beryllium oxide, magnesium oxide, crystalline and fused quartz, Pyroceram, Pyrex glass, and several types of graphite. In his comprehensive review of direct electrical heating methods for the measurement of thermal conductivity [119], he compared many sets of experimental data of various authors on the thermal conductivity of tungsten obtained by using direct electrical heating methods against our recommended reference data [1].

Flynn of NBS and O'Hagan of the Institute for Industrial Research and Standards, Dublin, Ireland [120] referred to our publication [1] as a thermal conductivity data source, so did Watson, Flynn, and Robinson [121], all of the Institute for Applied Technology, NBS.

Brush [122] of the Department of History and Institute for Fluid Dynamics and Applied Mathematics, University of Maryland, College Park, Marylind, in the section on heat conduction in his comprehensive review of the historical development of the kinetic theory of gases, listed 17 representative values for the thermal conductivity of hydrogen chronoligically dating from 1872 to the modern time. The "modern value" listed in his table is our recommended reference data [3].

Eckert, Sparrow, Goldstein, Scott, and Ibele [123] of the Department of Mechanical Engineering, University of Minnesota, Minneapolis, Minnesota referred to our publication [1] as providing further data on the thermal conductivity of selected solids.

White [124] of the Division of Physics, National Standards Laboratory, Chippendale, N.S.W., Australia referred to our publication [1] as a useful compilation of thermal conductivity data and recommended values.

Stigter [125] of the Laboratory for Physics and Meteorology, Agricultural University, Wageningen, Netherlands referred to our publication [1] as the source of thermal conductivity data for standard materials. For the intercomparison of samples of standard materials, he considered his relative method of measurement of thermal conductivity useful.

Men' and Chechel'nitskii [126] of the D. I. Mendeleev All-Union Scientific Research Institute of Metrology, Moscow, USSR referred to our publication [1] as a reference manual on thermal conductivity.

Kovalev, Petrov, and Sorokin [127] of the Institute of Semiconductors, Academy of Sciences of the USSR, Leningrad, USSR referred to our publication [1] as a thermal conductivity data source.

Reid, Sherwood, and Prausnitz of the Department of Chemical Engineering, Massachusetts Institute of Technology, Cambridge, Massachusetts stated in the Third Edition of their well-known textbook entitled "The Properties of Gases and Liquids: Their Estimation and Correlation" [128] that TPRC has presented a comprehensive review covering the thermal conductivity of the elements [3].

11. Reference Data Reproduced in Popular Handbooks Resulting in Broad Distribution and Innumerable Uses

Our recommended reference data for the thermal conductivity of selected solids, liquids, and gases [1] have been reproduced in the Handbook of Chemistry and Physics [129] in all its recent six editions since the 50th Edition published in 1969. Similarly our recommended reference data for the thermal conductivity of the elements [3] have been reproduced in this Handbook in its most recent 54th and 55th Editions covering 1973 to 1975. This popular Handbook with its annual editions is sold by tens of thousands of copies each year and reaches all libraries in the United States. Many scientists, engineers, professors, and even students have their own personal copies of this Handbook. Consequently, our recommended reference data hereby reach tens of thousands of users and the unrecorded uses of our recommended reference data are innumerable.

Part of our recommended reference data for the thermal conductivity of selected solids, liquids, and gases [1,2] have also been reproduced in the American Institute of Physics Handbook, Third Edition [130], and in Kaye and Laby's Tables of Physical and Chemical Constants, 14th Edition [131]. The AIP Handbook and Kaye and Laby's Tables are also very popular and used by countless scientists, engineers, professors, and students.

Ziebland of the Explosives Research and Development Establishment, Waltham Abbey, Essex, England reproduced our recommended reference data for the thermal conductivity of gaseous argon, liquid toluene, water, copper, gold, platinum, silver, fused quartz, and Pyrex glass [1] in his comprehensive review of the thermal conductivity of fluids [132].

Setty, Smith, and Yaws of the Semiconductor Research and Development Laboratory, Texas Instruments, Inc., Dallas, Texas reproduced some of our recommended reference data for the thermal conductivity of fluorine, chlorine, bromine, and iodine [3] in their article on the halogens [133].

III. USE OF TPRC'S CAPABILITY OF DATA ESTIMATION AND PREDICTION DEVELOPED IN THE COURSE OF CRITICAL EVALUATION, ANALYSIS, AND SYNTHESIS OF DATA

Over the years in the course of critical evaluation, analysis, and synthesis of property data, TPRC has developed an extensive capability of estimating and predicting property values whenever experimental data for the materials of interest are not available. Many of the thousands of technical inquiries received by TPRC in the years past were requests from governmental agencies, defense contractors, industrial organizations and others for estimated and predicted property values for newly developed technological materials and for materials on which no measurements have been made.

A recent technical inquiry from Lawrence Livermore Laboratory to TPRC may be cited here as a typical example of the use of such capability of TPRC. Mr. R. B. Baird, Contract Administrator of the Lawrence Livermore Laboratory, Livermore, California sent a Purchase Order (No. 2215500), dated 30 January 1975, to TPRC requesting the generation of estimated values for the thermal conductivity, heat capacity, and linear thermal expansion from 27 to 1900 C of BeO-UO_2 high-temperature nuclear reactor fuel elements, and requesting the answer to a technical question of how the thermal expansion coefficient of austenitic stainless steels is changed with the degree of cold working, among other requests. Since no experimental data are available for the thermal properties of BeO-UO_2 high-temperature nuclear reactor fuel elements, we generated the required property values by using techniques for data estimation and prediction developed at TPRC. We answered the question on the effect of cold working on the thermal expansion coefficient of austenitic stainless steels based on our technical experience, since no data are available. The resulting detailed tabulation of estimated values for the three thermal properties of BeO-UO_2 nuclear reactor fuel elements from 27 to 1900 C and the answer to the effect of cold working on the thermal expansion coefficient of austenitic stainless steels were forwarded to Mr. R. B. Baird on 12 February 1975, just a few working days after we had received his purchase order.

It is important to note that TPRC's estimated values are considered to be as accurate as experimental data produced by <u>accurate</u> measurements, but are generated at a small fraction of the cost and time required for producing experimental data. Should the thermal conductivity, heat capacity, and linear thermal expansion of BeO-UO_2 high-temperature nuclear reactor fuel elements from 27 to 1900 C discussed above be obtained by experimental determinations, instead of by estimation by TPRC, fifty to over one hundred times of cost and time would have been required. The element of time is especially important under urgent situations that demand quick response to critical needs, which no money can buy.

TPRC's capability of data estimation and prediction has been used to serve not only individual agencies and organizations but the Nation as a whole. A current program underway at TPRC/CINDAS may be mentioned here as an example. The current development of laser hardened materials against high power lasers is of vital importance to our national defense. In this development by the Army, Navy, and Air Force, data on many thermophysical properties of aerospace materials are urgently needed, but to produce such needed data experimentally would require many millions of dollars and many years of efforts. With its capability of data estimation and prediction as well as experience in data critical evaluation, analysis, and synthesis, TPRC/CINDAS is in a unique position to generate such urgently needed data at a fraction of the cost and time to meet the national needs.

IV. CONCLUSIONS AND RECOMMENDATIONS

The evidence provided in this report has clearly shown that the reference data generated by TPRC/CINDAS for NSRDS and DOD have been used extensively as standards in measurements and in many other applications. They have been used in important research and development programs and design calculations, essential to technological progress, the national economy, and defense. The reference data have been shown to be extremely useful and the public has been benefited greatly by TPRC/CINDAS' undertaking.

Furthermore, in the course of critical evaluation, analysis, and synthesis of property data, TPRC/CINDAS has developed a capability for data estimation and prediction, which has been extensively used to serve not only individual agencies and organizations but in meeting urgent national needs. This capability of TPRC/CINDAS has contributed greatly both in providing quick response capability to urgent needs for technical data and information and in saving time, money, and manpower for all concerned.

Thus, TPRC/CINDAS and similar organizations of its kind represent a unique national resource, as evidenced from the many examples. Such undertakings will result in propelling our national progress on many fronts at a much accelerated rate and at a fraction of the cost. It is hoped therefore that the support for such undertaking will be greatly increased in the critical years ahead so that we can get a bigger return on our research dollar.

Even though the impact of the usage of evaluated reference data on the national economy is obvious to those with the necessary background in science and technology, it would be perhaps of interest to some if the applications cited in this study could be translated into dollar savings through judicious estimation. Such an attempt was made but abandoned as having an inadequate basis to be considered meaningful. It suffices to say, however, that the estimated dollar value alone represented by the data cited in this study runs into tens of millions dollars. The investment required in the form of data evaluation costs would represent indeed a token fraction of this sum.

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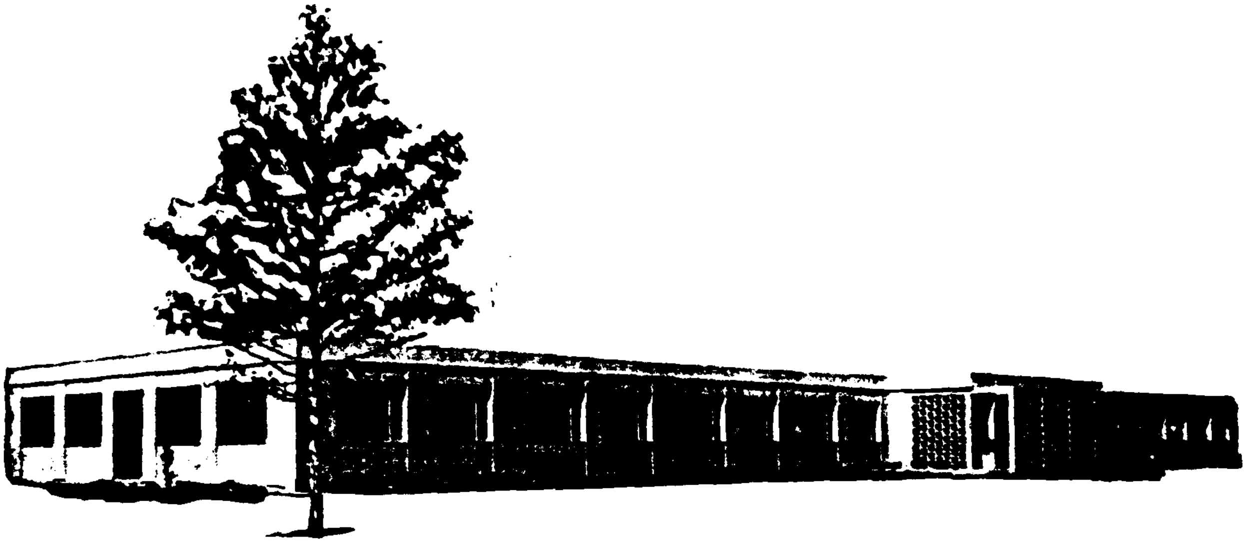

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